

Spontaneous Symmetry Breaking as the Mechanism of Quantum Measurement

Michael Grady

Department of Physics

SUNY Fredonia, Fredonia, NY 14063 USA

Abstract

It is proposed that an event that constitutes a quantum measurement corresponds to the spontaneous breaking of a symmetry in the measuring device over time.

The mechanism by which a quantum measurement is performed has been the subject of much controversy. The major problem is the lack of a precise mathematical description of the measurement process. If one insists on measuring devices themselves obeying quantum mechanics and evolving according to, say, the Schrödinger equation, then it is difficult to see how a measurement actually takes place, since a measuring device coupled to a system in a superposition of two states will itself end up in a superposition. Thus it is necessary to add an ad hoc measurement hypothesis to the “rules of quantum mechanics” whereby a measuring device is endowed with the special property of being able to break the superposition between states it is capable of measuring, and immediately after the measurement is only allowed (along with the system) to exist in an eigenstate of the measured quantity. Such an hypothesis works in practice to explain the results of experiments, but the description seems incomplete in that there is no mathematical description of the evolution of the measuring device and the system being measured from its state before to its state after the measurement, leaving open puzzles such as the exact process and space-time pattern of wave function collapse[1]. In addition, there seems no completely satisfactory relativistic generalization of measurement theory.

This basic problem in measurement theory is succinctly exemplified by the “Schrödinger’s Cat” paradox, where the absurdity of a measuring device remaining in a superposition is taken to the extreme by having a cat in a superposition of alive and dead states[2]. I think that most people would agree that it is absurd to think that the cat’s fate has not already been decided before one looks into the box.

Thus one is led to look for some reason by which one can prohibit measuring devices from being in superpositions of the quantities they are designed to measure. It is reasonable to assume that at least the individual components (i.e. atoms) which make up the measuring device still obey ordinary quantum mechanics. One idea is that since measuring devices tend to be large and contain large numbers of degrees of freedom, they are subject to random thermal fluctuations which will randomize those phases that would be necessary to establish and sustain such a superposition. For instance, it has been suggested that it is impossible to isolate a measuring device from its environment allowing for such random influences to enter from the outside[3]. Although this provides a possible explanation, it is somewhat unsatisfying in that by arguing that complexity is a basic requirement of a measuring device it would seem that any description of the measuring process would also be necessarily rather complex. It also does not provide a sharp dividing line between “ordinary quantum systems” which can exist in superpositions and “measuring devices” which cannot. Another possibility suggested recently involves decorrelation through coupling to higher modes in a string theory[4].

In the following it is suggested that what distinguishes measuring devices is that they contain spontaneously broken symmetries, the generators of which relate the eigenstates of the measured quantity. Not only this, but the process of measurement corresponds to the actual breaking of the symmetry as time evolves. The similarity between the measurement process and spontaneous symmetry breaking has been

previously pointed out by Ne'eman[5]. Anderson has also suggested a connection in that measuring devices generally consist of rigid materials which must contain broken symmetries[6]. Here it is suggested that they are one and the same and the ideas are expanded upon and developed.

What is needed is not just a system with a broken symmetry but one with an *adjustable parameter* which can take it from the symmetric to the broken phase. The measuring device is first coupled to the system being measured while in the symmetric phase. In this phase the measuring device attains whatever superposition the system being measured is in. Then the symmetry breaking parameter is adjusted until the symmetry breaks, throwing the entire combined system into one or another broken eigenstate. The superposition is broken due to the non-ergodicity of the broken ground states of the measuring device. In quantum mechanical language this translates into the existence of a superselection operator which selects for and separates the different broken ground states. By having a time dependent symmetry breaking parameter, the existence or non-existence of such a superselection operator is also made time dependent. Sherry and Sudarshan have previously utilized superselection operators in an effort to explain the lack of superposition in measuring devices[7]. If enough superselection operators are present, the system is found to behave essentially classically. However, in order to perform a measurement, the superselection operators must be turned off while the measuring device is coupled to the quantum system being measured. Here it is argued that breaking and unbreaking of a symmetry spontaneously provides such a mechanism for effectively turning on and off superselection operators.

As an example, imagine a device designed to measure the spin of a particle. The measuring device is represented by a scalar field theory based on a real scalar field, ϕ , with Lagrangian density

$$\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4 + \epsilon\phi\bar{\psi}\sigma_i\psi \quad (1)$$

where σ_i is a Pauli spin matrix in the non-relativistic case or $\sigma_i = \sigma_{\mu\nu}$ for a relativistic treatment. For this problem it will be assumed that there is known to be one fermion with creation operator ψ^\dagger located somewhere within the interaction region, which has been prepared in a state which is a superposition of eigenstates of σ_i , the spin component to be measured. Thus an explicit symmetry breaking term is presented to the scalar field, the sign of which is determined by the spin of the particle being measured. One begins at time $t = -T$ with $\epsilon = 0$, $\mu^2 > 0$. Then the systems are coupled by setting $\epsilon > 0$. Finally μ^2 is reduced until it becomes negative (at say $t = 0$) at which point the symmetry breaks. Before μ^2 becomes negative, configurations with $\bar{\phi} > 0$ and $\bar{\phi} < 0$ (where $\bar{\phi}$ represents the spatial average of ϕ) both exist, which are somewhat correlated with the spin-up and spin-down states of the fermion. The fact that both exist means that a superposition is present. As $\mu^2 \rightarrow 0$ the system becomes more and more sensitive to the explicit symmetry breaking. Finally, for $\mu^2 < 0$ configurations are separated into two distinct ensembles representing the two broken ground states, with no tunneling between them. At

this point the superposition is broken and the system can be said to be definitely in one state or the other, i.e. the system is now in a mixed state. Why? Because superpositions of spontaneously broken vacuum states are not allowed states in field theory. Such states violate the cluster property, for instance. To see this consider a hypothetical symmetric superposition of two broken vacua, one with $\langle \phi \rangle = v$ and the other with $\langle \phi \rangle = -v$. This superposition will have $\langle \phi \rangle = 0$, but $\lim_{x \rightarrow \infty} \langle \phi(0)\phi(x) \rangle = v^2$. From the path integral point of view one is supposed to no longer sum over all configurations but only over one subset corresponding to a given broken vacuum, and excitations around it.

Technically, these ensembles are only completely ergodically isolated if the measuring device contains an infinite number of degrees of freedom. Real measuring devices contain a large but finite number of degrees of freedom. However, if the tunneling time is very large, say many times the age of the universe, it seems reasonable to assume that the behavior will be the same as that of an infinite system. Very much the same issue arises in early universe phase transitions. Consider the electro-weak phase transition, for example. Here it is crucial that a specific symmetry broken vacuum arises, rather than a superposition of different broken vacua, in order to leave the photon massless. One needs a single component of the Higgs field to condense. This must be the case even if the universe is not infinite, and is assumed to be the case for both infinite and finite universes.

The identification of a measuring event with spontaneous symmetry breaking opens the door to a mathematical description of the actual measurement process. It is the same as the dynamical breaking of a symmetry over time. This is a well posed, but perhaps not completely understood problem in quantum field theory. A complete understanding of this problem could explain the pattern of wave-function collapse even in the relativistic case. All that is needed for this is to use a relativistic quantum field theory to represent the measuring device. In this picture the wave function collapse apparently occurs along the hypersurface on which $\mu^2 = 0$, i.e. the hypersurface on which the symmetry breaking takes place.

As stated previously, a time dependent symmetry breaking can be expressed in the path integral description by letting μ^2 be a function of time ($\mu^2 > 0$ for $t < 0$ and $\mu^2 < 0$ for $t > 0$). Since the $t > 0$ portion is still infinite (or nearly infinite) the symmetry is broken, even though it is not broken over the entire space-time. It is clear that the exact state immediately prior to $t = 0$ will be strongly correlated with the various possible broken states for $t > 0$, however all of the sub-ensembles will look very similar for $t \ll 0$. This shows how essentially similar initial states can evolve into distinct and disjoint final states. The symmetry breaking chooses one of several possible histories for the system as it dynamically chooses its ground state. Thus the proper description of a physical situation which includes a measurement event contains only a subset of all possible states, those that are included in a single $t > 0$ broken ground state, which carries with it, through correlations across the $t = 0$ hypersurface, a subset of possible preexisting states which nevertheless connect to nearly all possible states of the spatial wave function at large negative times,

i.e. a superposition, consistent with the state's preparation (initial time boundary condition). An analogous situation which aids in visualization of this picture is that of a ferromagnet in a spatial temperature gradient so that $T > T_c$ (here T is the temperature and T_c is the critical temperature) for $x < 0$ and $T < T_c$ for $x > 0$. The right half of the magnet will be spontaneously magnetized and, since by itself it is an infinite system there will be no tunneling. However the left half will be unmagnetized, i.e. all possible magnetizations will be included in the ensemble.

It is interesting to consider whether real measuring devices are amenable to such a description. The bubble or cloud chamber for instance contains a fairly obvious symmetry breaking as an essential ingredient of its operation. The supersaturated vapor or supercooled liquid is a translationally invariant metastable state lying on top of multiple ground states consisting of condensed droplets or bubbles, which can occur at any place in the spatial volume. Individual ground states break translational invariance. The coupling of the medium to the electric charge leads to a correlation between particle position and droplet position which influences the choice of broken vacuum. The localization of the droplet which occurs when the symmetry breaks carries with it the localization of the wave function of the charged particle because the interaction causes a high correlation between the two positions, and since a superposition of bubbles in two different positions is not an allowed state after symmetry breaking, neither will be a superposition of the correlated particle positions. Although it may be less obvious in other systems, it is conceivable that all measuring devices contain a symmetry which is dynamically broken upon measurement in a similar way.

Since dynamical spontaneous symmetry breaking apparently allows a physical system to evolve from a pure state to a mixed state, it may also play a role in the information loss paradox present in the formation of and subsequent evaporation of black holes[8].

Finally, such a picture leads to certain speculations as to the nature of time in quantum mechanics and quantum field theory. The spontaneous breaking of symmetries explains why a system has several possible distinct histories (corresponding to a mixed state) rather than always a superposition of all possible histories, however it does not explain why one particular history is chosen rather than another in a given case. In other words there is still a "roll of the dice". This could be inherent to the quantum concept of reality, however if the usual picture of a superposition is modified somewhat an element of determinism can be introduced. One can picture a superposition as a system which is very rapidly switching between all possible states in the ensemble (for a field theory this would be all possible classical field configurations consistent with boundary conditions). Thus ordinary time would in some sense be connected to a "Monte Carlo" time in such a way that a very small interval of ordinary time involved many steps in Monte Carlo time over which the field configuration was randomly changed, including past values of the field. In this case the fields really would have a particular value at any one instant and the direction of symmetry breaking would depend on the exact field configuration present

at the exact moment of symmetry breaking. However it is far from clear whether such a radical picture of time evolution can be made consistent with fundamental properties such as relativistic covariance and causality.

It has been suggested that spontaneous symmetry breaking events constitute quantum measurements. Because consistency of field theory prohibits superposition of different spontaneous broken vacuum states, the dynamical breaking of a symmetry over time results in the transformation of a pure state into a mixed state. This will break the superposition of any quantum state coupled strongly enough to the broken symmetry generator. Thus measuring devices are a special class of quantum systems which contain an adjustable symmetry breaking parameter which can take the system into and out of the spontaneously broken state.

Acknowledgement

It is a pleasure to acknowledge the hospitality of the Theoretical Physics Group at the Tata Institute of Fundamental Research, where a portion of this work was completed. This work was partially supported by a grant from the Indo-US Sub-commission on Education and Culture.

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